

Design of lab-scale downdraft gasifier for biomass gasification

G Suresh Kumar^{1*}, AVSSKS Gupta², M Viswanadham³

1 Assistant Professor, Mechanical Engineering Department, ICFAI Foundation for Higher Education, Dontanapally, Shankarpally Road, Hyderabad, India, 501203

2 Professor, Mechanical Engineering Department, College of Engineering, Jawaharlal Nehru Technological University, Kukatpally, Hyderabad, India 500085

3 Professor, Center for Environment, Institute of Science & Technology, Jawaharlal Nehru Technological University, Kukatpally, Hyderabad, India 500085

*skgrandhi@gmail.com

Abstract. Biomass gasification is a cost effective, efficient and eco-friendly source of alternate energy. The gasification efficiency depends on several parameters like equivalence ratio, gasification agent, gasifier configuration, etc. Downdraft gasifier is a most suitable gasifier for biomass gasification due to inherent advantages like feedstock flexibility, better process control, low tar formation, and simple construction. The aim of this paper is to conduct a comparative study of different configurations and design a 5kW lab scale throatless biomass gasifier using an analytical method.

Keywords: Downdraft gasifier design, specific gasification rate, gasifier efficiency, throatless gasifier

1. Introduction

Gasification is a thermo chemical process of converting solid fuel into gaseous fuel. Biomass gasification is an attractive option for power generation due to abundant availability of feedstock, ease of operation, eco-friendliness and better process control. The primary goal of biomass gasification is optimal energy conversion of the solid biomass into combustible gaseous product known as producer gas. The gasification efficiency depends on several factors like equivalence ratio, biomass properties, gasification agent, and gasifier configuration. Depending on the direction of air flow gasifiers are grouped into three types viz., i) Downdraft, ii) updraft and iii) cross draft gasifier. Figure 1 shows the classification of various gasifiers. Downdraft gasifier is also called co-current gasifier. In this, the air is introduced at the center portion of the reactor and drawn from the downside. The oxidation and reduction zones will be just below the point of air inlet. Even though the overall efficiency is relatively less than updraft gasifier, it has a lesser tar forming tendency and higher gas loading capacity. Downdraft gasifiers are further divided into throated (Imbert type) and throatless (Open core) gasifiers. The construction of down draft gasifiers and their relative merits and demerits are given in table 1.



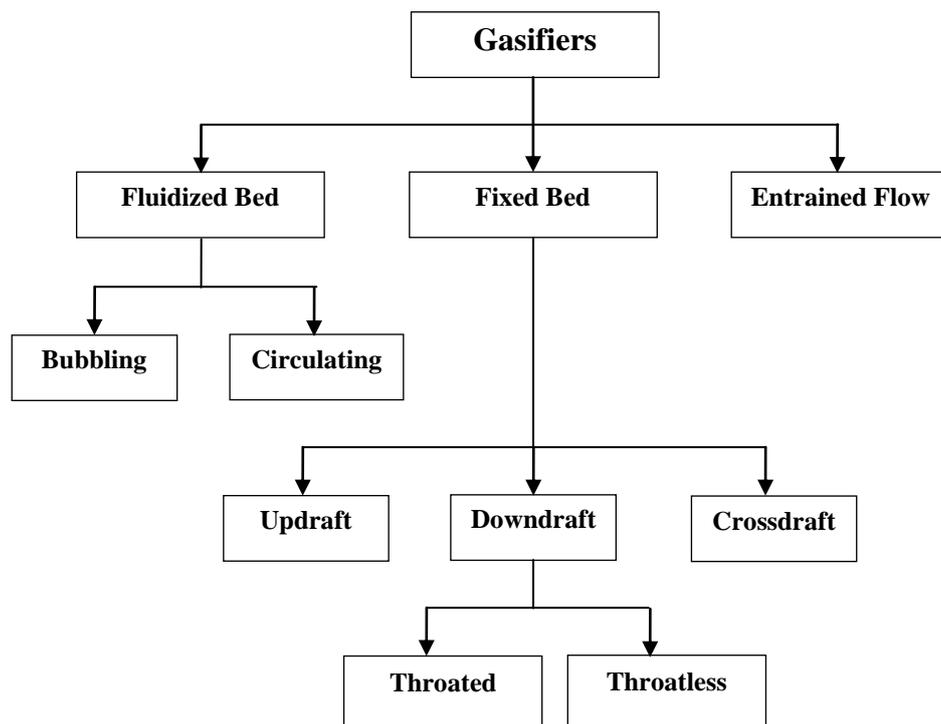


Figure 1. Classification of Gasifiers.

Table 1. Types of gasifiers and their relative advantages and disadvantages.

Gasifier Type	Updraft	Downdraft	Crossdraft
Typical Layout			
Advantages	<ul style="list-style-type: none"> • Small pressure drop • Good thermal efficiency • Low slag formation 	<ul style="list-style-type: none"> • Fuel flexibility • Less sensitive to tar and char content • Good response to fluctuating loads 	<ul style="list-style-type: none"> • Short design heights • Very good response to fluctuating loads • Flexible gas production
Disadvantages	<ul style="list-style-type: none"> • Highly sensitive to tar and moisture content in fuel • Poor response to fluctuating loads 	<ul style="list-style-type: none"> • Tall design heights • Not feasible for smaller particles • Lower thermal efficiency 	<ul style="list-style-type: none"> • Highly sensitive to slag formation • Large pressure drop

Quality of syngas depends on heat content, and tar content. Many researchers have worked on enhancing the efficiency of gasifier by implementing design modifications to downdraft gasifier. Virmond et al. [1] studied the effect of size and shape of feedstock on efficiency in different types of reactors. They concluded that finer and low density feedstock will have bridging problems especially, in the throated gasifiers. Throatless gasifiers are suitable for unrestricted movement of such feedstock. Mukunda et al. [2] achieved higher efficiency by allowing air distribution, increasing insulation and recirculating gas within the reactor there by utilizing the sensible heat in the gas to dry the biomass. Barrio et al. [3] modified air distribution system and injected air at the center of the reactor cross section so that air distributed uniformly to all sides of the reactor. They also used a perforated grate with manual actuation to clear the ash contents continuously and to ensure smoother bed movement. Dasappa et al. [4] used multilevel air injection system to increase the residence time to promote tar cracking and gas yield. Ojolo et al. [5] developed twin outlets system for effective ash discharge and tested the gasifier in natural and forced draught conditions. They found that forced draft system gives better efficiency with minimum char formation. Liinanki et al. [6] used a double conical hopper and rotating grate. Double conical hopper reduced the bridging problem in the pyrolysis zone while rotating grate reduced ash agglomeration problem. Altafini et al. [7] used recirculation of producer gas and partially combusted to increase the reactor temperature and thereby reducing tar formation and increasing efficiency.

2. Gasification parameters and design factors

While designing a gasifier the following factors are to be considered;

2.1. Characteristics of fuel

Characteristic of fuel plays a significant role in the design of gasifier. The important characteristics are energy content, moisture content, size and shape of feed stock, ash content, density, etc. Downdraft gasifiers are suitable for moisture content of up to 20% [8]. Higher energy content and higher fuel density necessitate lesser reactor size. Throated gasifiers will have bridging effect if the feedstock size is large such as briquettes and usually pellets are recommended for such gasifiers. On the other hand, throatless gasifiers are suitable for a variety of feedstocks with different shapes and sizes.

2.2. Equivalence Ratio (ER)

Equivalence ratio is the ratio of actual air quantity to stoichiometric air quantity. It will determine whether the process takes is pyrolysis, gasification or combustion. It also influences the composition of syngas. A higher value of ER will result in low concentration of H₂ and CO, and increased tar production [9]. ER ranges between 0.2-0.4 for majority of fuels.

2.3. Operating temperature

As temperature increases, efficiency increases. However the energy losses also increase with increase in temperature. Hence proper insulation of the reactor chamber is required to reduce the energy losses.

2.4. Residence time

Residence time plays an important role in the gasification. Higher residence time tends to decrease the formation of tar compounds and increases carbon conversion efficiency and hence the gas yield.

2.5. Type of Reactor

Reactor is the most crucial element of a gasification system. Selection of reactor depends on the type of application such as process heat, power generation, etc. Crossdraft and updraft gasifiers are quick to respond to fluctuating loads and are suitable for longer operating times when compared to downdraft gasifier [9].

2.6. Superficial Velocity

It is defined as a ratio of the syngas production rate at normal condition and the cross-sectional area of the gasifier. It affects the gas production, gas energy content, power output, and tar production rates. It depends on feedstock packing factor which creates resistance to air flow and is independent of gasifier dimensions. Low values of superficial velocity result in a relatively slow pyrolysis process which results in high yields of char and unburned tars [10].

2.7. Cross-sectional area of reactor

Cross-sectional-area of the gasifier depends on the rate of fuel consumption, and specific gasification rate. The area of reactor and grate increases with FCR and decreases with SGR.

2.8. Height of reactor

The height of the reactor determines the operational time and the amount of gas that can be produced from reactor column. Usually, the combustion zone moves down at a speed of 1 to 2 cm/min [11]. As the height of the reactor column increases more resistance will be offered to air flow and requires a powerful draught system.

2.9. Height of fuel bed

Height of the bed is same as that of reactor. As the height of bed increases the greater is the resistance to the air flow. The main advantage of thicker bed is, it decreases the downward movement of the bed and increases the residence time. This will help in reduced tar formation and increased gas yield.

2.10. Air-flow requirement

Air flow depends on type of draught system used in the gasifier. In case of natural draught system the air flow is determined by superficial air velocity and porosity factor of the bed.

2.11. Grate area

Grate area is usually the cross-sectional area of the reactor. The specific gasification rate depends on the grate area.

3. Materials and Method

A lab scale throat-less downdraft gasifier for gasification of wood pellets is designed for 2 hours batch operation. Design calculations are based on design procedure given in Belinio et al [12]. After obtaining the necessary dimensions models are developed in AutoCAD and subsequently the gasifier is fabricated. A step by step design procedure is depicted in the flowchart shown in figure 3. Necessary initial conditions and assumptions are given in table 2.

Table 2. Initial design conditions and assumptions for the design of gasifier.

Assumptions and Initial Design Conditions	
Type of Gasifier	Downdraft (Throatless)
Type of fuel	Wood Pellets
Calorific Value of fuel	15 MJ/kg
Density of fuel	370 kg/m ³
Gasification Efficiency	60%
Specific Gasification Rate	100 kg m ⁻² h ⁻¹
Equivalence Ratio	0.3
Stoichiometric A/F Ratio	6.5 kg of air kg ⁻¹ wood
Random packing factor (cubes)	0.7

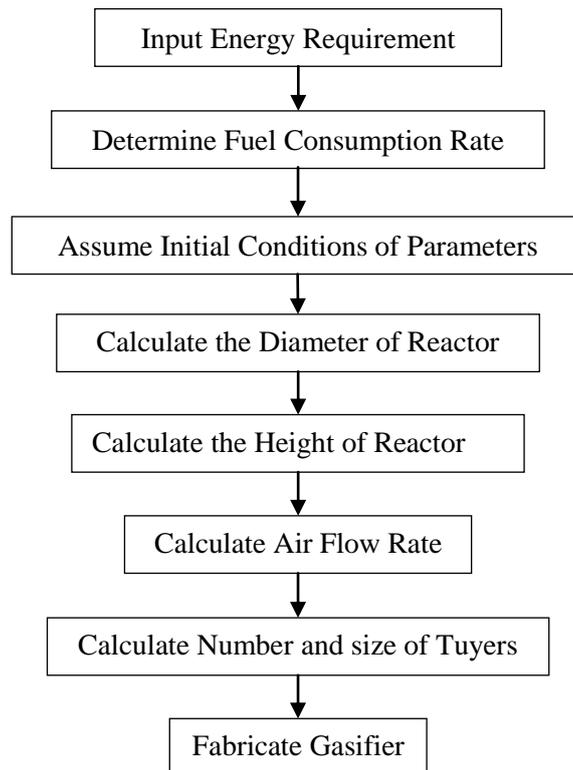


Figure 2. Step by step design procedure.

3.1. Energy Required

It is the amount heat energy to be produced by the gasifier.

$$Q_{net} = 5 \text{ kW}$$

3.2. Fuel Consumption Rate (FCR)

It is the ratio of energy to be produced to the calorific value of the fuel. Considering gasification efficiency of 60% the fuel consumption rate is given as;

$$FCR = \frac{Q_{net}}{CV \times \eta_g} = \frac{5000 \times 3600}{15 \times 10^6 \times 0.6} = 2 \text{ kg/hr}$$

3.3. Specific Gasification Ratio (SGR)

This parameter represents the rate at which the fuel is converted into producer gas per unit area of the gasifier.

$$SGR = \frac{\text{Weight of the feedstock material (kg/hr)}}{\text{Grate area (m}^2\text{)}}$$

3.4. Grate Area (A)

It represents the cross-sectional area of the reactor. It is ratio of FCR to SGR.

$$A = \frac{FCR}{SGR} = \frac{2}{100} = 0.02 \text{ m}^2$$

3.5. Gasifier Efficiency

It is the ratio of the energy content in the produced gas to the energy content in the burned fuel.

$$\text{Gasifier Efficiency} = \frac{\text{Calorific Value of gas} \times \text{Volume of gas}}{\text{Heating value of Fuel} \times \text{FCR}} \times 100$$

3.6. Reactor Diameter (D)

It is the diameter of cross-section of reactor where the fuel is burned. It depends on the fuel consumption rate and specific gas production rate.

$$D = \left[\frac{1.27 \times FCR}{SGR} \right]^{1/2} = \left[\frac{1.27 \times 2}{100} \right]^{1/2} = 0.159 \text{ m} \approx 0.16 \text{ m} = 160 \text{ mm}$$

3.7. Reactor Height (H)

It depends on quantity of the fuel to be maintained in the reactor which in turn depends on gasification rate and operating time.

$$H = \frac{SGR \times T}{\rho_b} = \frac{100 \times 2}{370} = 0.54 \text{ m} = 540 \text{ mm}$$

3.8. Air Flow Rate (AFR)

It is the amount of air to be supplied to the reactor. It depends on the equivalence ratio (ϵ), FCR and stoichiometric air (SA) quantity. SA is the minimum amount of air required for complete burning of kg of biomass.

$$AFR = \frac{\epsilon \times FCR \times SA}{\rho_{air}} = \frac{0.3 \times 2 \times 6.5}{1.25} = 3.12 \text{ m}^3/\text{hr} = 8.67 \times 10^{-4} \text{ m}^3/\text{s}$$

3.9. Superficial Air Velocity (V_s)

It is defined as a ratio of the air flow rate at normal conditions to the cross sectional area of the gasifier. It is independent of the reactor dimensions and influences the amount of tar and char produced.

$$V_s = \frac{4 \times AFR}{\pi D^2} = \frac{4 \times 3.12}{\pi \times 0.16 \times 0.16} = 155.2 \text{ m/hr} = 0.043 \text{ m/s}$$

Usually a forced draught is required to meet the air supply requirements gasification.

3.10. Diameter of the tuyer (d_t)

Tuyer is the air inlet point to the reactor. The air is to be supplied uniformly across reaction zone and therefore, multiple tuyers are arranged around the circumference of the reactor. Area of the tuyer is the ratio of total cross sectional area of the air supply to the number of tuyers. Assuming an air flow of 4 m/s and 3 tuyers equally spaced along the circumference of the reactor, the diameter of the tuyer is given by;

$$d_t = \left[\frac{1.27 \times AFR}{v_a \times Z} \right]^{0.5} = \left[\frac{1.27 \times 8.67^{-4}}{4 \times 3} \right]^{0.5} = 0.0096 \text{ m} \approx 10 \text{ mm}$$

However, considering availability of standard material a 1" diameter pipe is used for tuyers.

3.11. Hopper volume (V_h)

Hopper volume is obtained by subtracting the reactor volume from the total volume of fuel.

Total volume of fuel,

$$V_f = T \times \frac{\dot{m}_f}{(\rho_b \times P_f)} = 2 \times \frac{5}{(370 \times 0.70)} = 0.039 \text{ m}^3$$

Where V_f = Volume of the fuel
 V_h = Volume of hopper
 V_r = Volume of reactor
 P_f = Random packing factor for cubes

$$V_h = V_f - V_r = 0.039 - 0.011 = 0.028 \text{ m}^3$$

3.12. Hopper height (H_h):

The hopper is a conical shaped vessel with base diameter equal to the diameter of the reactor core. Assuming a top diameter (d_2) of 300mm;

$$H_h = \frac{3 \times V_h}{[\pi(r_1^2 + r_1 r_2 + r_2^2)]} = \frac{3 \times 0.028}{[\pi(0.08^2 + 0.08 \times 0.15 + 0.15^2)]} = 0.65 \text{ m}$$

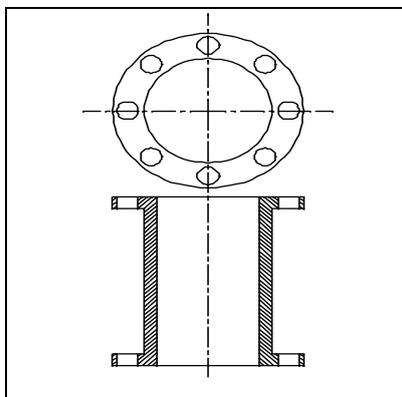


Figure 3. Autocad model and fabricated gasifier.

4. Conclusions

A lab-scale throatless downdraft gasifier for gasification of wooden pellets is designed for a batch operation of 2 hours. Crossdraft gasifiers are quick to respond load fluctuations but carry a disadvantage of slag formation. Updraft gasifiers provide higher efficiency but suffer the problem of poor response time. Downdraft gasifiers are a better choice where fuel flexibility, good response to fluctuating load and reasonable efficiency are the primary requirements. Specific gasification rate (SGR) which determines the gasifier configuration and performance is an assumed value. As SGR increases the cross sectional area of reactor decreases and height of gasifier increases. The increase in reactor height poses resistance issues to the air flow. Thus there exists an optimal SGR value such that the efficiency is increased and resistance to the air flow is decreased. The future work can be optimization of the gasifier configuration and parameters depending on operating conditions, feedstock properties, and application.

5. References

- [1] Virmond E, Rocha J, Moreira R and José H 2013. *Brazilian Journal of Chemical Engineering* **30**, p197-230.
- [2] Mukunda H, Dasappa S, Paul P, Rajan N and Shrinivasa U 1994 *J. Energy for Sustainable Development*, p 27-38.
- [3] Barrio M, Hustad J, and Fossum M, 2001 *Progress in thermochemical biomass conversion* p426-440.
- [4] Dasappa S, Paul P, Mukunda H, Rajan, N, Sridhar G and Sridhar H 2004 *Current Science* **87**, p908-916.
- [5] Ojolo Sand Orisaleye J 2010 *J Energy and Power Engineering* **4**.
- [6] Liinanki L, Svenningsson P J and Thessen G 1985 *Proceedings of 2nd International Producer Gas Conference, Bandung, Indonesia*.
- [7] Altafini C R, Wander P R and Barreto R M 2004 *J. Biomass and Bioenergy* **27**, p467-476.
- [8] Wei-Cheng Y, Ye S, Siming Y, Soong H S, Zheng-Hong L, Yen W T and Chi-Hwa W 2018 *J. Cleaner Production* **5** doi: 10.1016/j.jclepro.2018.01.009
- [9] Susastriawan A P, Harwin S and Purnomo 2017 *J. Renewable and Sustainable Energy Reviews* **76** p 989-1003
- [10] Anjireddy B and Sastry R C 2011 *Int. J. Chem. Engineering and Applications* **2** p 425-433
- [11] Rajiv V, Bhagoria J L and Mehta C R 2012 *Ultra Engineer* **1** p 35-41
- [12] Belonio A T 2005 *Rice Husk Gas Stove Handbook* (Iloilo: Central Philippine University)